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DETECTION OF UNEVEN FLATNESS ON LIQUID SURFACE

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Abstract: This research is aimed at improving accuracy of stereolithography (Rapid prototyping) system. The objective of this paper is to detect the flatness of freeform liquid surface. The principle of measurement is performed by obtaining grating image of total reflection from freeform liquid surface. The detection is performed by two steps, coarse detection and fine one. Coarse detection is used for searching widely deformed area and fine detection is used for verifying flatness of freeform liquid surface. The phase detection of grating image is based on Linear Digital Phase-Locked Loop (L-DPLL).

Keywords: Rapid prototyping, Total reflection, Flatness

1 INTRODUCTION

Stereolithography system is known as rapid prototyping equipment to fabricate mechanical parts for prototypes. The principle of fabrication process is to pile up thin sliced shape. By hardening liquid photoresin into solid polymer layer by layer, it can produce parts of complicated shape easily. It shortens a trial period in product development drastically. On the other hand, as it uses layering method, stair steps occur on the surface of prototypes and it deteriorates accuracy. To satisfy the industrial demand for improving accuracy, thinner layer thickness is applied at present.

Flatness of each layer is strictly demanded according as thinner layer is applied. Although stereolithography is fabricated by solidifying freeform liquid surface, it is necessary to make sure the flatness of free form liquid surface at fabrication process if higher accuracy is demanded and thus thinner layer is used.

The problem of uneven flatness of freeform liquid surface occurs at building process. One of the problems is known as trapped volume phenomenon (Fig. 1). If the shape of a part is like a cup, the inner liquid surface is likely to be mound shape at recoating process because that the liquid resin of inner contour shape is isolated from the outside of resin.

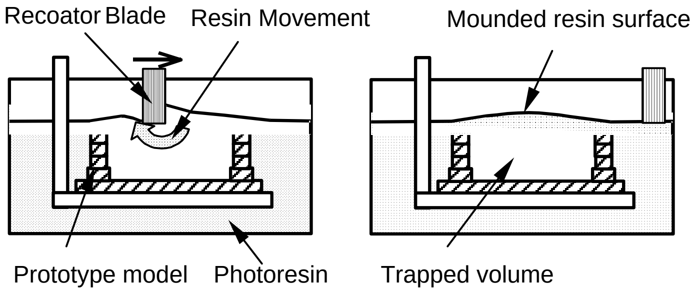


Figure 1. Occurrence of uneven flatness

The state of uneven flatness should be detected to assure flatness of layers of stereolithography part. The current stereolithography system does not measure the flatness of freeform liquid surface. Usually a certain point of liquid surface is only monitored to maintain the liquid surface level. This paper proposes the detection system for uneven flatness of freeform liquid surface.

2 UNEVEN FLATNESS DETECTION SYSTEM

For our measurement purpose, there are several requirements to be satisfied to install an uneven flatness detection system into stereolithography equipment.

1) Wide area should be measured: The size is from 100 mm X 100 mm to 1,000 mm X 1,000 mm. It depends on how large prototype can be manufactured.
2) Transparent resin surface should be measured.
3) Tolerance of flatness ranges from a few µm to hundreds µm. But actual resin surface can vary few mm.
4) The working area, which is perpendicular to the resin surface, should be avoided to install a measurement instrument.

Although profile measurement method using grating projection is promising [1], most cases of researches assume that the grating image are from the diffused light source reflected by a object and transparent object cannot be measured using these configuration.

Taking these requirements into account, we have developed uneven flatness detection system using total reflection images from liquid surface (Fig. 2).

The position of the grating plate and the CCD camera do not interrupt working area that laser beam can irradiates above from the resin surface.

To simplify the problem, two dimensional layout is explained.

Let us think about three coordinates system. One is the global coordinate system, which the axis *X* lies in the reference plane.

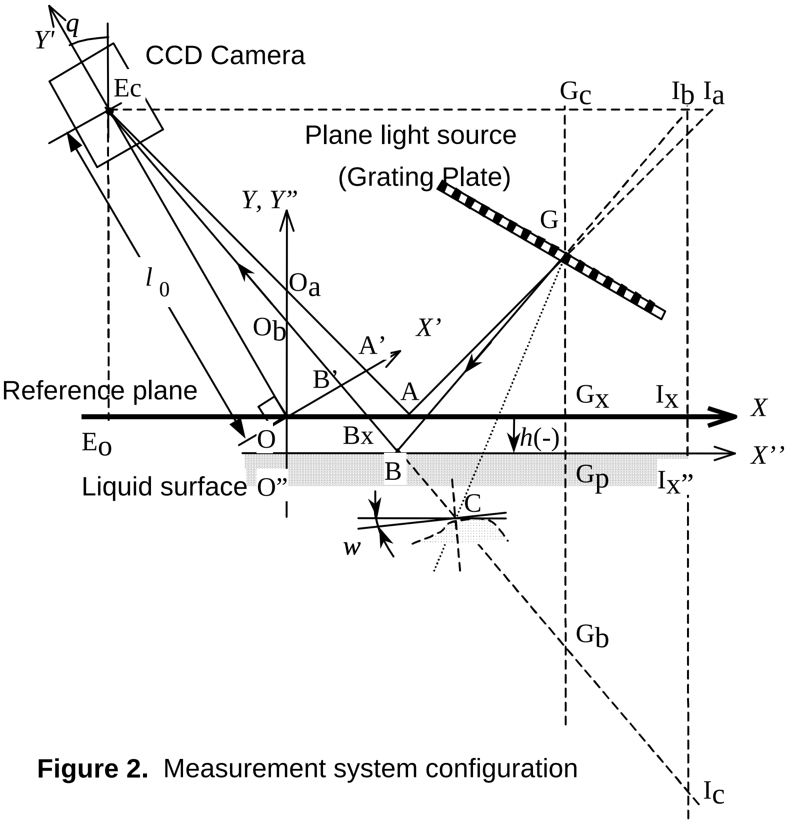


Figure 2. Measurement system configuration

The second is Image plane coordinates system with *X'* and *Y'* axis. The image from CCD camera can be treated as image on axis *X'*. The origin of the coordinate is shared with global coordinate system. The distance of camera is l_0 and inclined angle is *q*.

The third is liquid surface coordinate system that the axis *X"* crosses a point of designated liquid surface and the distance between axis *X'* and *X"* is defined as displacement height *h*.

2.1 Measurement Principle

The image A' = (x'_a, 0) is the reflected image of the point G on the grating plate. It is the case when liquid surface is on the reference plane. The image B' = (x'_b, 0) is the reflected image of the same point G when the liquid surface is moved to *X"* by *h*. Let us calculate the reflection point A. By comparing similar figures, point A is obtained. In the same way, the position B_x is obtained as follows;

$$\Delta E_C E_0 B_x \propto \Delta O_b O B_x , \Delta E_C E_0 A \propto \Delta O_a O A$$

$$\overline{OB_x} = \frac{\overline{OO_b}\,\overline{OE_0}}{\overline{E_C E_0} - \overline{OO_b}} = \frac{l_0 x'_b}{l_0 \cos q - x'_b \sin q} , \quad \overline{OA} = \frac{\overline{OO_a}\,\overline{OE_0}}{\overline{E_C E_0} - \overline{OO_a}} = \frac{l_0 x'_a}{l_0 \cos q - x'_a \sin q} \tag{1}$$

The image A' is invariant if the point G=(x_G, y_G) of grating plate keeps the following relation,

$$\Delta OAO_a \propto \Delta G_x AG$$

$$\therefore \frac{y_G}{x_G} = \frac{\overline{OO_a}}{\overline{OA}} = \frac{l_0 \cos q - x'_a \sin q}{l_0 \sin q + x'_a \cos q} = f(x'_a) \tag{2}$$

If points on the grating plate satisfy the equation $\mathrm{a}x_G + \mathrm{b}y_G = \mathrm{c}$, the point G on the grating plate is obtained from image A'.

$$\begin{cases} y_G = f(x'_a)\, x_G \\ \mathrm{a}x_G + \mathrm{b}y_G = \mathrm{c} \end{cases} . \qquad \therefore \{x_G, y_G\} = \left\{ \frac{\mathrm{c}}{\mathrm{a} + \mathrm{b}f(x'_a)}, \frac{\mathrm{c}f(x'_a)}{\mathrm{a} + \mathrm{b}f(x'_a)} \right\} \tag{3}$$

Liquid surface of axis *X"* makes mirror image I_c of I_b, the position of reflected point B can be calculated from the relation,

$$\overline{I_b I_{x"}} = \overline{I_{x"} I_c}$$

$$\therefore \overline{O"B} = \frac{1}{2}\left(\overline{OE_0} + \overline{OB_x} + \overline{B_x I_x}\right) - \overline{OE_0} = \frac{l_0 x'_b + h(l_0 \sin q + x'_b \, cosq \,)}{l_0 \cos q - x'_b \sin q} \qquad (4)$$

By comparing similar figures, height h is obtained as follows;

$$\Delta OO_b B_x \propto \Delta G_C G_b E_C$$

$$\frac{\overline{OB_x}}{\overline{E_C G_C}} = \frac{\overline{OO_b}}{\overline{G_C G_b}} = \frac{\overline{OO_b}}{l_0 \cos q + y_G + 2h}. \quad \therefore h = \frac{l_0 (x'_a - x'_b)(l_0 \cos q + y_G)}{2(l_0 \sin q + x'_b \cos q)(l_0 \cos q - x'_a \sin q)} \qquad (5)$$

As the movement of grating image from x'_a to x'_b is translated into phase shift Df_{sr}, the height h can be expressed by the phase shift such as,

$$\Delta f_{sr} = x'_b - x'_a$$

$$h = \frac{-l_0 \Delta f_{sr}\left(l_0 \cos q + y_G\right)}{2\left(l_0 \sin q + \left(\Delta f_{sr} + x'_a\right)\cos q\right)\left(l_0 \cos q - x'_a \sin q\right)} \qquad (6)$$

If the tangent plane of the reflection point at liquid surface is inclined at an angle w, the relation satisfies ∠BGC = 2w. Although this system configuration cannot distinguish the each reflection points C that lies on the line $E_C I_C$, these points are displaced one from the reference point or a point on the inclined surface. Therefore, the monitoring of phase shift from the reference plane can detect not only displacement but also the inclination of liquid surface at the same time.

2.2 Uneven flatness detector

The phase detection of grating image is based on Linear Digital Phase-Locked Loop (L-DPLL) [2]. The detection is performed by two steps, coarse detection and fine one. Coarse detection is used for searching widely deformed area and fine detection is used for verifying flatness of freeform liquid surface (Fig. 3).

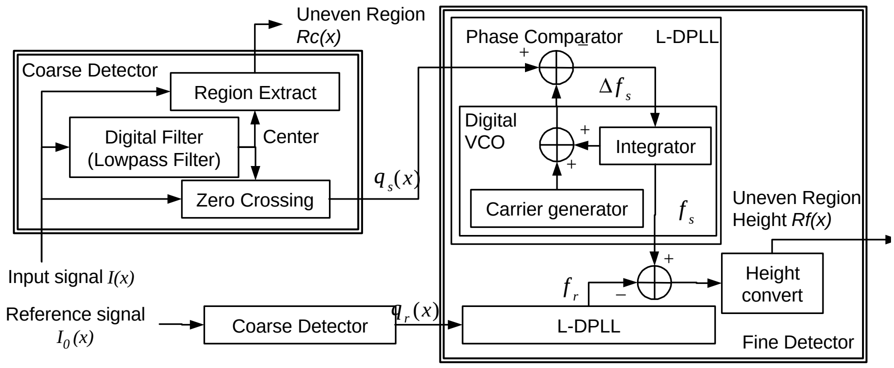


Figure 3. Block diagram of uneven flatness detector

Fig. 4 shows the representative example of coarse detection process. As widely deformed surface diffuse reflect beam, it diminishes the intensity rapidly. Region extract is performed by finding lower intensity region. The window that has the property of number of pixels for checking at one time and criteria of intensity for checking the image input signal. Window moves along the center of the intensity of current input signal. If the region is found that all the intensity of pixel images are within the window, it is extracted as a coarse uneven flatness region.

Fine detection process compare the phase between reference image signal and input image signal.

It is calculated as phase shift Df_{sr} and calculated as height if needed.

Note that the reflected grating image produces easily degenerated and ghosted image, which means the number of grating is increased or decreased by the unwanted reflecting images if the surface is widely deformed. The number of grating is compared and checked between input signal and reference signal beforehand whether the signal can be transferred to the fine detector or not.

3 EXPERIMENT

Fig. 5. shows the representative example of experimental results of coarse detection and fine detection. The white area in (a2) is the result of coarse detection, where the liquid surface is widely deformed and grating image is disappeared. Fig.5 (b3) shows the phases of line segment from reference image and test image. f_r and f_s is the phase of reference and test image respectively. Df_{sr} is the phase difference of two phases.

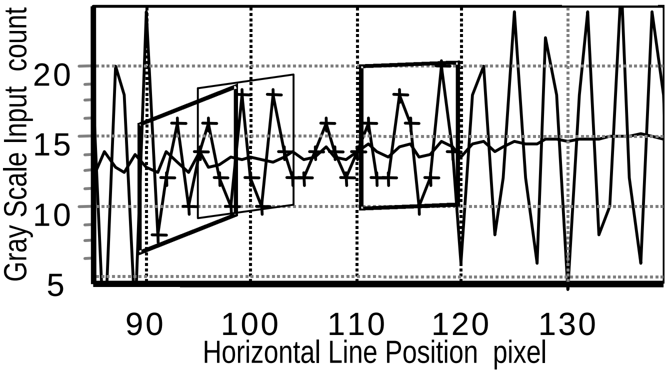
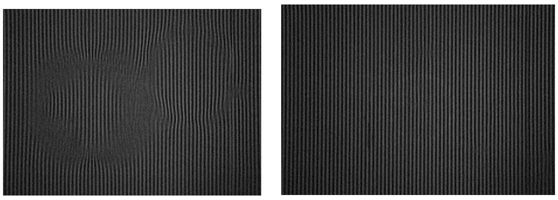
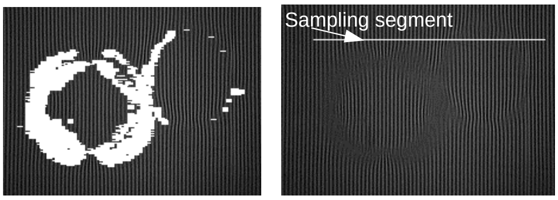


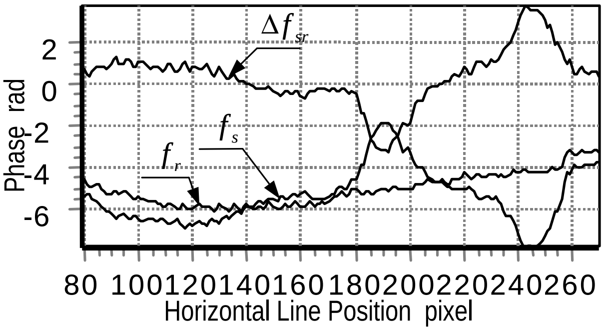
Figure 4. Windowing and coarse detection



(a1) Image Source (b1) Reference Image



(a2) Detected Region (b2) Test Image



(b3) Phase output

Figure 5. Experimental results: (a) coarse detection, (b) fine detection

4 CONCLUSIONS

Following results were obtained:

1. Total reflection grating image is effective for detecting uneven flatness of freeform liquid surface of stereolithography system,.
2. The experimental results showed that the uneven flatness area of free form liquid surface could be successfully detected using coarse and fine detection algorithm.

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